Argonne National Laboratory

k CALCULATIONS FOR

22 ZPR-III FAST REACTOR ASSEMBLIES

USING ANL CROSS-SECTION SET 635

by W. G. Davey

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by

W. G. Davey*

Idaho Division

*Assigned to Argonne National Laboratory from the United Kingdom Atomic Energy Authority

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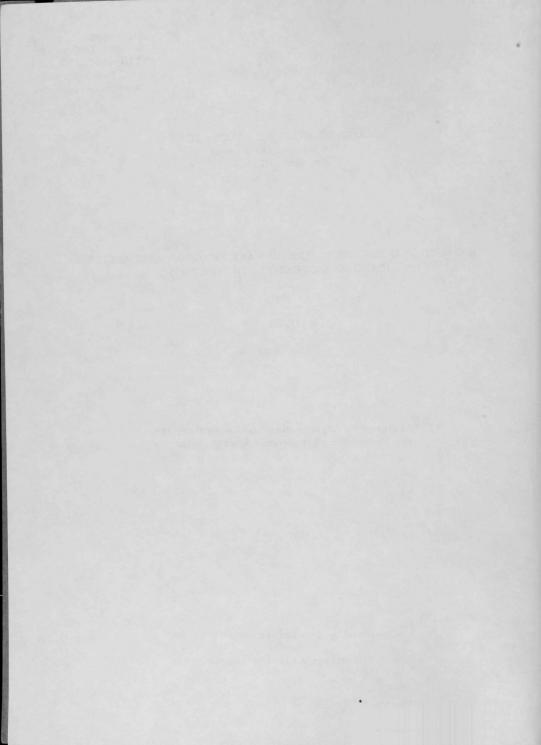


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k CALCULATIONS FOR 22 ZPR-III FAST REACTOR ASSEMBLIES USING ANL CROSS-SECTION SET 635

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ABSTRACT

The Yiftah, Okrent, and Moldauer cross-section set (ANL Set 135) has been modified to include new measurements of ν and α for U^{235} , and also to include, in an approximate manner, Hummel, Rago, and Meneghetti's corrections for flux depression at resonance energies in aluminum and stainless steel. This modified set, ANL Set 635, has been used to compute values of k for 22 ZPR-III assemblies of widely varying composition. The DSN neutron transport code was used in spherical geometry and the S4 approximation; shape factors were used to convert from cylindrical to spherical geometry. Seventeen of the calculated values of k lie within \$1% of a mean value of 1.003, and the remaining 5 lie within ±2%. In terms of prediction of critical mass, it appears that the procedure used here can achieve an accuracy of 5% to 10% for a wide range of U235-fueled assemblies.

1. INTRODUCTION

The main objectives of Yiftah, Okrent, and Moldauer in constructing their published $^{(1)}$ multigroup cross-section set (ANL Set 135, widely known as the YOM Set) was to use, as far as was possible, only microscopic nuclear data, and to document all choices and assumptions made. In a comparison $^{(1)}$ between measured and calculated critical masses of a range of ZPR-III assemblies for which data were available at the time of the study, it was shown that the disagreement in terms of $k_{\rm eff}$ was, in general, only about 1% and was at most about 2%. In addition, it was shown that the use of conservative values for ν for U^{235} (which were not the best which could be deduced from the basic data but which were plausible in view of experimental errors) further reduced the disagreement between calculation and experiment.

Unfortunately, this fairly satisfactory situation did not continue when the range of ZPR-III experiments was extended to large reactors containing considerable quantities of nonfertile diluents, such as steel, aluminum, K CALCULATIONS FOR 22 2PR IN PAST REACTOR ASSEMBLIES USING ANL CROSS-SECTION SET 435

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Unfortunately, this fairly satisfactory situation did not continue when the renge of ZFR-III experiments was extended to large reactors containing considerable quantities of nontertile diluents, such as steel, significant.

carbon, and oxygen. (2-4) In these cases, the calculated values of k (not using the conservative values of ν for U^{235}) were about 5% too high. Recent work by Meneghetti(5,13) and Hummel and Rago(6) has shown that for materials such as aluminum, steel, sodium, and oxygen, which have strong resonances in the energy region of interest, group cross sections must be obtained in a manner that accounts for the depression of the flux in the resonances. Allowance for these effects has reduced the disagreement between calculation and experiment, (5,13) but if only this correction is introduced the discrepancies in certain cases still remain as high as 3% or 4% in k.

However, there are other points for which recent work has indicated that the original YOM calculations can be improved. In the field of analysis, calculations by Loewenstein and Main, (7) and experiments (20,21) have shown that the shape factors which should be used in deriving the masses of equivalent spherical reactors from those of the experimental cylindrical reactors (which is necessary as multigroup transport theory calculations are only practicable in one-dimensional geometry) in some cases are appreciably different from those previously used. (8) Also, new measurements show that the capture-to-fission ratios (α) for U²³³, U²³⁵, and Pu²³⁹(9) and the ν value for U²³⁵(10-12) are considerably different from the YOM data.

As each of the modifications (i.e., in resonance shielding effects, shape factors, and α and ν values) can change the calculated values of k in certain assemblies by up to 1%, it was believed that these should be introduced into a further study of the ZPR-III data.

For this study, the YOM data were modified to give a cross-section set listed at Argonne as ANL Set 635, and this was used to examine 22 ZPR-III assemblies of widely varying composition.

2. OBJECTIVE OF THIS STUDY

The work of Hummel and Rago and Meneghetti clearly shows that when reactors contain materials with strong resonances, then, due to the superposition of resonances, an exact evaluation of group cross sections must be made for the mixture of elements. Consequently, as all practical reactors contain steel and sodium, exact calculations must use cross-section sets which are unique to each core composition. In addition, as there are spatial variations of neutron spectrum, it is possible that in exact calculations group cross sections should vary throughout the reactor.

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Although the amount of work involved in this procedure is, no doubt, justified for examination of a specific reactor design, a large amount of computation is concerned with parametric studies of projected reactors. In these studies, a large number of reactors of different compositions and sizes must be examined briefly in order to find which reactors are worthy of detailed study, and the work involved in exact calculations for these reactors could be prohibitive. Although such a procedure is known to be inexact, there is a strong case for determining if a single cross-section set can predict the critical sizes of a variety of reactors with adequate accuracy.

Hence, the objective of the present work is to see if a single crosssection set, based upon the basic nuclear data, can predict the critical masses of a wide variety of ZPR-III assemblies with reasonable accuracy.

It is recognized that, even if such a cross-section set is successful in attaining this objective, there is no expectation that it can predict other parameters with similar accuracy, and, indeed, it may be grossly in error in computation of, for example, perturbation effects.

3. CONSTRUCTION OF ANL SET 635

The ANL cross-section set 635 consists of the 16-group YOM Set (ANL Set 135) with modified values of α and ν for U^{235} and of σ transport (σ_{tr}) and σ elastic removal (σ_{er}) for aluminum and the components of stainless steel, i.e. Fe, Ni, and Cr.

3.1 α for U^{235}

This quantity has been measured by Diven and Hopkins $^{(9)}$ over an energy range from 30 kev to 1 Mev with about $\pm 7\%$ accuracy.

Values of α for each of the YOM groups in the range of the measurements were taken from a smooth curve drawn through the experimental points of Diven and Hopkins. These were then used with the YOM values of σ_f for U^{235} to give new $\sigma(n,\gamma)$ U^{235} data. For YOM groups 1, 2, 3, 15, and 16, the YOM $\sigma(n,\gamma)$ U^{235} were used. The two sets of data are compared in Table I.

It can be seen that the new values of $\sigma(n,\gamma)$ are lower than those provided by the YOM data above about 0.3 Mev (i.e., groups 4, 5, 6) and higher than those from the YOM data below this energy. As many of the ZPR-III assemblies are not very dilute, they have spectra which peak at about this energy, and in these cases (e.g., assemblies 23, 10, and 24) the change in k caused by the change in $\sigma(n,\gamma)$ U²³⁵ is small (0.2% or less), but in very dilute assemblies (e.g., assemblies 14 and 29) the value of k is decreased by about 1%.

Although the amount of work involved in this procedure is, no doubt justified for examination of a specific reactor design, a large amount of computation is concerned with parametric studies of project-d reactors. In these studies a large number of reactors of different compositions and sizes must be examined briefly in order to find which reactors are worthy of detailed study, and the work involved in exact calculations for these reactors could be prohibitly. Although such a proxedure is known to be inexact, there is a strong case for determining it a single cross-section set can predict the extitual sizes of a variety of reactors with adequate accuracy.

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U rol o 1.6

This quantity has been measured by Diven and Hopkins (9) over an energy range from 30 key to 1 Mey with about 175 accuracy.

Values of a for each of the YOM groups in the range of the mease were taken factor through the experimental points of Diversing Hopkins. These were then used with the YOM values of of for U^{CB} to give new of (n, y) U^{CB} data of for YOM groups and 16, the YOM of (n, y) U^{CB} were used. The two sets of data are compared in Table I.

It can be seen that the new values of s(n,y) are lower than those provided by the YOM data above about 0.3 Mer (n.e., groups 4.3.6) and higher than the YOM data below this outry. As many of the ZPR-III assemblies are not very dilute, they have spectra which beak at about this energy, and in these cases (e.g., assemblies 23, 10, and 24) the change in h k daused by the change in n(n y) U. 10 is small (0.2% or less), but in very filter assemblies (e.g., assemblies 14 and 29) the value of k; is decreased by about 150.

Table I $\label{eq:anl_set} \mbox{ANL SET 635 AND YOM DATA FOR } \sigma(n,\gamma) \mbox{ AND } \nu \mbox{ U^{235}}$

Group	Lower Energy	σ(n, γ) (barns)	ν	
(j)	Limit (E _L) (Mev)	Set 635	УОМ	Set 635 ^a	YOM
1	3.668	0.020	0.020	2.71	3.15
2	2.225	0.035	0.035	2.71	2.84
3	1.350	0.058	0.058	2.60	2.67
4	0.825	0.102	0.115	2.53	2.58
5	0.500	0.167	0.193	2.48	2.52
6	0.300	0.200	0.240	2.46	2.48
7	0.180	0.305	0.296	2.44	2.45
8	0.110	0.397	0.370	2.43	2.44
9	0.067	0.549	0.483	2.43	2.43
10	0.0407	0.731	0.624	2.42	2.43
11	0.0250	0.954	0.803	2.42	2.42
12	0.0150	1.150	1.003	2.42	2.42
13	0.0091	1.396	1.249	2.42	2.42
14	0.0055	1.732	1.689	2.42	2.42
15	0.0021	2.092	2.092	2.42	2.42
16	0.0005	3.825	3.825	2.42	2.42

aThese are the conservative v values of YOM

3.2 v for U²³⁵

The data for ν of U^{235} as a function of neutron energy has been greatly extended and improved in accuracy by the work of Moat \underline{et} \underline{al} ., Butler \underline{et} \underline{al} ., and Diven and Hopkins, and it is apparent that these data should be carefully analyzed to obtain the maximum information. For example, it is now clear that ν of U^{235} is not a linear function of neutron energy from thermal energies to 14 Mev,(10) and it is possible that it may not be linear in the energy range of interest in fast reactors. However, this point is not yet clear, and the new data are not inconsistent with the conservative values tabulated by YOM (these are given approximately as $\nu(E) = 2.42 + 0.1E$). Consequently, in order to avoid unnecessary duplication of data, it was decided to use the conservative YOM values in the present study. These data are given in Table I.

A feature of these values that probably will not be substantiated by the new measurements is the equality of ν in groups 1 and 2. However, as only about 2 to 3% of the flux lies in group 1, and also as the final analysis of the experimental data will certainly require some modification of all the ν values, it was decided to accept these data.

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These are the conservative v values of YOM

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The data for so of \$V^{12}\$ as a function of neutron energy has been greatly extended and improved in accuracy by the work of Most 25 21. X. Butler eval. and Direct and Hopkins, and it is apparent that these data should be constituted and rice which is not a linear function of newton energy from the matter which is not a linear function of newton and be linear in the chargins to 14 Mev. (10) and it is resident that it may the paint is not yet clear, and the new data are mot inconsistent with the conservative values tabulated by YCM (these are given approximately an idea; if was the conservative of a void in accessary qualitation of data; it was decided (consequently, in ordered a void inaccessary qualitation of data; it was decided (consequently, in ordered a void inaccessary qualitation of data; it was decided (consequently, in ordered a void vancessary qualitation of data; it was decided (consequently in ordered a void vances and the presentation.)

A factor of more webset that probably will not be substantiated by the new measurements in the equality of o in groups 1 and at However, it as only about 2 to 35 of the flexibles in group 1, and size as the frail near and the experimental detailed in textising require a my modification of all the president in was decided to accept these Late.

As has been shown by Yiftah, Okrent, and Moldauer, (1) use of the conservative ν values rather than of the best YOM data decreases the calculated values of k by about $1\frac{1}{2}\%$.

3.3 Resonance-corrected Cross Sections for Aluminum and Stainless Steel

The IBM-704 ELMOE code of Hummel and Rago carries out a fundamental mode analysis by means of hundreds of neutron groups and detailed elastic-scattering matrices, so that resonances are accurately described. The code thus yields the material buckling of the core under consideration and the detailed variation of flux with energy. Gross group cross-sections for neutron transport and elastic scattering are then derived.

As stated in Section 2, the ELMOE calculation should be carried out for the correct core mixture and a given mixture which contains resonance materials, such as aluminum, stainless steel, sodium, and oxygen, should have a unique set of cross sections, but the present study is concerned with determining the usefulness of a single cross-section set. Here we follow the work of Meneghetti in that we use aluminum and stainless steel cross sections evaluated, respectively, for the predominantly aluminum and stainless-steel-diluted ZPR-III Assemblies 23 and 32. Hummel and Rago and Meneghetti showed that this procedure overestimates the correction applied for resonance flux depression, since the minima in the cross section of a given element are frequently filled in by other elements. The reader is referred to these reports for discussions of this phenomenon.

Thus, in neither the aluminum nor the stainless steel data in Set 635 is allowance made for the presence of other resonance materials. The cross sections for sodium, oxygen, and all other materials (excluding U²³⁵) were taken unmodified from the YOM set.

The corrections to the YOM aluminum and stainless steel data are taken from Table II of Meneghetti. (13) They are presented in Table II of this report. These correction factors were applied to the YOM data for Al, Fe, Ni, and Cr to give the cross sections used in Set 635. As, in each group, the same stainless steel correction factor was applied to the Fe, Ni, and Cr YOM cross sections, these data can only be used for calculating the effects of stainless steel. They cannot be used for evaluating the effects of Fe, Ni, and Cr separately.

Meneghetti has shown that for ZPR-III Assemblies 23, 29, 30, 31, and 32, the effect of introducing the corrections listed in Table II is to reduce the calculated value of k.

As has been shown by Yillah, Okrent, and Moldauer, (1) use of the conservative by values rather than of the best YOM data decreases the call culated values of k by about 1-20.

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Moneghetts has shown that for ZPR-III Assemblies 23, 29, 30, 31 and 32, the effect of introducing the corrections listed in Table II as to reduce the calculated value of k.



Table II

RATIO OF MODIFIED (SET 635) TO UNMODIFIED (YOM)

CROSS SECTIONS FOR ALUMINUM AND STAINLESS STEEL

		Ratio						
Group	Lower Energy	Alumi	num	Stainles	s Steel			
(j)	Limit E _L (Mev)	Transport	Elastic Transfer	Transport	Elastic Transfer			
1	3.668	where (1)a value	Your (1) Yalin	(1)	(1)			
2	2.225		0.162 1.11 -190	0.86	0.81			
3	1.350	2.00 0.95 1.90	0.216 1.25 -770	0.97	1.14			
4	0.825	2-48 0.85 2-105	0.332 1.02 339	0.91	1.03			
5	0.500	2-97 0.945 2-107	0.404 1.11 -445	0.95	1.11			
6	0.300	T-17 0.94 1.950	0-450 1.02 -429	0.86	0.78			
7	0.180	3-32 0.76 9-902	0.414 0.93 -470	0.94	1.03			
8	0.110	5-02 0.61 3-042	0-492 0.84 -57	0.84	0.99			
9	0.067	5-95 0.475 2-141	0-690 0.61 -431	0.64	0.80			
10	0.0407	2.78 0.67 1.862	0-309 0.68-209	0.95	0.95			
11	0.0250	6.34 0.24 1.522	0.721 0.36 260	0.49	0.75			
12	0.0150	0.75 0.71 0.523	0.091 ~0 0	0.67	0.73			
13	0.0091	1-13 0.97 1-096	0-121 1.0001	0.98	0.98			
14	0.0055	1-51 (1)	0-161 (1)	(1)	(1)			
15	0.0021	(1)	(1)	(1)	(1)			
16	0.0005	(1)	(1)	(1)	(1)			

^aFor groups 1, 14, 15, and 16, no ELMOE calculation was made and here the ratio is assumed to be unity.

4. CALCULATIONS WITH SET 635

The method used in the present calculations was (a) to correct the experimental critical mass for the effects of heterogeneity, core boundary irregularities, and the ZPR-III center gap to give the critical mass of a homogeneous regular system, usually a cylinder; (b) except in the few cases where the experimental cores were spherical, a shape factor was next applied to give the critical mass of an equivalent homogeneous spherical reactor; (c) and to carry out spherical geometry, DSN transport theory calculations in the S4 approximation to obtain the effective multiplication factor k. Ideally, a k of unity should be obtained. From these calculations, spectra and fission rates can be derived.

The experimental critical masses and corrections are given in Table III.

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RATIO OF MODIFIED (SET 635) TO UNMODIFIED (YOM) CROSS SECTIONS FOR ALUMINUM AND STAINLESS SEEF!

'For groups 1, 14, 15, and 10 no ELMOE calculation was made, and here the total's assumed to be unity.

CALCULATIONS WITH SET F

The method used in the present calculations was (a) to correct the conservations and one of the culture of hereroganeily, core boundary tree pulsarities and the ZPR-IR couter gan to give the critical mass if a boundary cases where the critical mass is a cylinder (b) except in the few mass where the critical mass of an equivalent only a shape (actor was next applied to give the critical mass of an equivalent hoursequence and the critical reactor (c) and to early out spicenesh geometry, DNN transport theory calculations in the St approximation to obtain the effective multiplication income is the content of the conte

the experimental or intel masses and corrections are given in

Table III

EXPERIMENTAL CRITICAL MASSES AND CORRECTIONS^a

2 DD - 111	F		Experin	nental Corre	ctions to	Critical Mass
ZPR-III Assembly Number	Experimental Critical Mass M (kg)	$\frac{(\triangle M/M)^b}{(\triangle k/k)}$	Hetero- geneity (kg)	Irregular Boundary (kg)	Center Gap (kg)	Corrected Experimenta Mass (kg)
2A	147.7	3.3	+ 3.8	-0.1	-1.1	150.3
5	159.5	4.1	+ 4.6	-0.1	-1.2	162.8
6F	131.1	3.8	+ 3.4	-0.1	-1.1	133.3
9A	146.2	4.4	+ 5.8	-0.1	-1.3	150.6
10	155.8	5.3	+ 9.1	-0.1	-1.7	163.1
11	240.6	7.0	+16.6	-0.2	-3.0	254.0
12	176.8	5.5	+ 5.8	-0.1	-1.8	180.7
14	136.0	3.8	+ 2.6	-0.1	-1.1	137.4
16	204.8	4.8	+10.2	-0.2	-2.0	212.8
17	156.5	4.5	+ 3.5	-0.1	-1.4	158.5
20	431.0	5.0	+15.2	-0.2	-3.0	443.0
23	258.1	4.5	+ 9.8	-0.2	-3.0	264.7
24	460.7	9.4	+35.7	-0.4	-6.0	490.0
25	581.6	7.2	+37.7	-0.4	-6.0	612.9
29	420.7	5.4	+24.0	-0.2	-3.0	441.5
30	394.9	5.7	+22.5	-0.2	-3.0	414.2
31	463.0	5.6	+25.9	-0.2	-3.0	485.7
32	227.5	4.2	+ 9.7	-0.2	-3.0	234.0
33	238.0	4.2	+ 9.7	-0.2	-3.0	244.5
34	503.0	5.0	+24.9	-0.4	-6.0	221.5
35	505.4	4.8	+33.5	-0.4	-6.0	532.5
36	242.7	4.3	+10.4	-0.2	-3.0	249.9

aReferences for these data are given in Appendix I

4.1 Corrections for Heterogeneity, Core-boundary Irregularities, and the ZPR-III Central Gap

The basic units for construction of the ZPR-III assemblies are small slabs of fuel and diluent of approximate dimensions $2 \times 2 \times \frac{1}{4}$ in. It has been shown both experimentally (14) and theoretically (15) that, because of the finite thickness of the pieces, the fission rates are not uniform through a typical cell, but are higher in the fuel. As a consequence, the experimental heterogeneous assembly is more reactive than a similar homogeneous system. Experimental corrections for this effect are made by measuring the reactivity change on bunching the fuel pieces and also on substituting some $\frac{1}{16}$ -in.-thick fuel pieces and then extrapolating to find the effect of zero-thickness fuel. These reactivity effects are of the order of 1% in k (i.e., 5% to 10% in critical mass).

^bThis ratio is that between a fractional change in critical mass (added at the boundary of the reactor with no change in composition) and the corresponding fractional change in k.

The correction for core-boundary irregularities arises because cylindrical and spherical assemblies must be approximated in ZPR-III by means of modules of square cross section. Experiments (14) in which smaller modules were utilized have indicated that the correction is small; the experimental assembly is less reactive than the ideal system by only about 0.01% to 0.02% in k (i.e., about 0.1% in critical mass).

The center-gap correction in ZPR-III occurs because it is constructed in two halves and there is an inhomogeneity in the center plane, consisting of the fronts of the drawers used to hold the fuel and diluent pieces (about 0.16 cm of stainless steel or aluminum) plus any clearance between the halves. It has been estimated that these cause the experimental assembly to be less reactive than the ideal system by about 0.1% to 0.2% in k (i.e., about 1% in critical mass).

It can be seen that by far the most important of these corrections is that made for heterogeneity. Because of uncertainties in extrapolation to zero fuel thickness and in the validity of the substitutions, it is possible that this correction may be uncertain to about 0.2% to 0.3% in k. Errors in the other corrections are probably small when compared with this error.

Because of the lack of experimental data for some reactors, it was necessary to estimate the magnitude of some corrections by considering the results obtained with similar reactors.

4.2 Shape-factor Corrections

The shape factor (SF) is defined as the ratio of the spherical critical mass of a system to that of an assembly of the same core and blanket composition but of different geometry (usually cylindrical).

It has long been known that the SF is a function of the length-to-diameter ratio (L/D) of a cylindrical core, and it appears reasonable that it should also be dependent upon other reactor parameters such as core size and core and blanket composition. Until recently, the only data available were experimental values for small dense cores [e.g., see Loewenstein and Okrent.]⁽¹⁶⁾ Although a recent theoretical study by Loewenstein and $Main^{(7)}$ and some ZPR-III measurements^(20,21) have extended our knowledge to some large dilute cores, it still does not seem possible to select a SF unambiguously.

The author understands that some of the numerical data given by Loewenstein and Main⁽⁷⁾ may be subject to revision; hence, the procedure adopted here was to use Loewenstein and Main's data to define the variation of SF with L/D and to obtain absolute values using experimental data only.

The correction for core boundary transdistance areas because extinctions and aphartes assemblies must be approximated in ZER-III by means of modules of equate cross acquire. Experimentalists which smaller modules were unlined have indicated that the corrections's small, the experimental sasembly is less reachys than the ideal ereturn by only about 0.01% to 0.02% in a (100, about 0.1% in critical mass).

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two 0.25 in k (i.e. about 15 in critical mass)

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extended our Loswigt as some targe diffus cores, it still does not agent
possible to scient a SF unaminguously.

The author understands that some of the numerical data given by Lowenstoin and Main! I may be arbijent to revision, hence, the procedura adopted here was to use Lowenstoin and Main's data to define the variation of sir with L/D and to chief absolute values using experimental data only.

Loewenstein and Main show that the general variation of SF with L/D is similar for the four cases investigated, all the curves giving a maximum SF close to an L/D of 0.9. Accordingly, a mean curve giving this variation was derived from the data of Loewenstein and Main, the curve being normalized to a value of unity at L/D = 0.9.

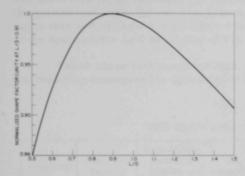


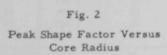
Fig. 1. Normalized Shape Factor as a Function of L/D

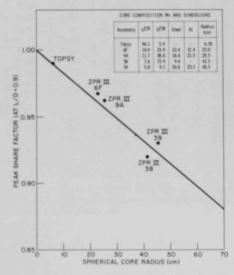
The shape of this mean curve (see Fig. 1) is within about $\frac{1}{2}\%$ of the exact Loewenstein and Main values over the L/D range from 0.7 to 1.2.

Most of the experimental data on shape factors has been summarized by Loewenstein and Main, with the only data given for U²³⁵-fueled, thick uranium-reflected systems being for Topsy and the spherical ZPR-III Assemblies 6F and 9A. These data have now been extended for spherical versions of the large ZPR-III Assemblies 24

and 31 (called Assemblies 38 and 39, respectively). With the five values available, the only well-defined trend is of decrease of SF with increasing core size, the SF being roughly a linear function of core radius.

This variation is shown in Fig. 2, the shape factors being calculated for cylinders with L/D values of 0.9.





Thus, as little data are available, the possible variation of shape factor with reactor composition, etc., has had to be ignored, and only a crude dependence upon core size can be introduced.

The procedure for obtaining shape factors to permit computations was therefore (a) to calculate the radius of a sphere of the same volume as the cylindrical core; (b) use Fig. 2 to find the peak shape factor corresponding to this radius (L/D = 0.9); and (c) to correct this shape factor to that of the appropriate L/D by means of Fig. 1.

These shape factor corrections are given in Table IV together with the resulting homogeneous spherical critical masses.

Table IV
THE SHAPE FACTOR CORRECTION

Assembly No.	Assembly Volume (liters)	Approximate Radius of Sphere of Same Volume (cm)	Peak Shape ^a Factor	L/D	f(L/D)b	Actual Assembly Shape Factor ^c	Critical Mass of Sphere ^d (kg)
2A	56.4	24	0.96	0.97	0.997	0.96	144
5	60.8	24	0.96	0.94	0.999	0.96	156
6F	49.9	23	0.96	Sphere	-	-	133
9A	66.6	25 ×	0.96	Sphere	-	1200	151
10	70.1	28 25.63	0.95	1.04	0.990	0.94	153
11	134.9	32 31.8	0.94	0.88	1.000	0.94	239
12	100.5	29	0.95	0.87	1.000	0.95	172
14	77.3	26	0.96	0.99	0.996	0.96	132
16	116.4	30	0.95	0.91	1.000	0.95	202
17	89.0	28	0.95	0.93	1.000	0.95	151
20	377.4	45	0.92	0.96	0.998	0.92	408
23	148.5	33	0.94	0.84	0.998	0.94	249
724	324.6	43 41.9	0.93	0.93	1.000	0.93	456
25	432.6	47 47-01	0.92	0.90	1.000	0.92	564
29	451.5	48	0.92	0.79	0.992	0.91	402
30	356.4	44	0.92	0.80	0.994	0.91	377
31	425.0	47	0.92	0.73	0.980	0.90	437
32	131.0	32 31.56	0.94	1.17	0.972	0.91	213
33	136.9	32	0.94	1.14	0.977	0.92	225
34	574.4	52	0.91	0.94	0.999	0.91	475
35	663.9	54	0.91	1.00	0.995	0.91	485
36	138.1	32	0.94	1.44	0.920	0.87	217

aAt L/D = 0.90, from Fig. 2

bFrom Fig. 1

* Band on 18.07 long x 17.41 dimentio. 28 sams to the present

Radius

C(Peak Shape Factor) x [f(L/D)]

^dProduct of the shape factor and the corrected experimental mass given in Table III

4.3 The DSN Calculations

The homogeneous spherical critical masses given in Table IV were used together with the core compositions to compute the expected critical radii. DSN, S4 calculations were then carried out to obtain k effective for each system. In all cases 30-mesh intervals were used, 15 being evenly spaced in the core and 15 in the reflector. In five cases, the calculations were repeated with double the number of mesh points, but this produced less than 0.03% change in k, and it was concluded that 30-mesh intervals described the system adequately.

Details of the reactor compositions are given in Appendix II.

5. RESULTS OF THE CALCULATIONS

The k values obtained from the DSN calculations are given in Table V together with a summary of the reactor compositions.

None accurate Appendix

Table

▼

REACTOR COMPOSITIONS AND COMPUTED VALUES OF K

1	Assembly	Ratio		Appro	ximate Vo	imate Volume Percentage of Material in Core ⁸							Deviation	Equivalent Deviation in
	No.	<u>U</u> 238 UZ35	U235	U238	Steel	Al	Na	С	0	Mo	Zr	. Computed keff	from Mean k of 1.003 ^b	Critical Mass
I	23	0.07	9.3	0.7	9.2	42.8	100	- 200	1000	200	4.99	1.012	+0.009	+4.1
-1	ZA	0.07	14.0	1.0	27.8	31.4						1.012	+0.009	+3.0
4	6F	1.1	14.0	15.9	12.4	31.4				14.5		1.008	+0.005	+1.9
- 1	5	1.1	14.0	15.9	12.3	31.4						1.010	+0.007	+2.9
-	29	2.0	5.0	10.0	24.9	24.4			14.5			1.005	+0.002	+1.1
-1	30	1.5	5.9	9.0	24.7	23.4			7.3	10.00		1.014	+0.011	+6.3
4	. 31	1.6	5.8	9.1	24.8	23.5						1.013	+0.010	+5.6
-	34	2.2	4.7	10.3	24.8	25.5		9.1				1.000	-0.003	-1.5
	9A	3.2	11.7	38.0	14.4	21.5				1000	1000	1.003	0.000	0.0
	20	3.1	6.1	19.0	14.5	25.1				5.0	4.3	0.997	-0.006	-3.0
2 -	- 10	4.9	11.9	57.9	19.5			100	7.37			1.000	-0.003	-1.6
FΤ	11	7.5	9.5	71.7	9.2							0.995	-0.008	-5.6
7	24	9.6	7.6	72.9	9.4							0.996	-0.007	-6.6
1	8	10.3	7.2	74.2	9.2							0.991	-0.012	-8.6
	35	0.07	4.1	0.3	50.0		35.6		4.2			0.985	-0.018	-8.6
	36	5.3	9,4	49.5	12.8		18.2				100	0.995	-0.008	-3.4
	33	0.07	9.3	0.7	64.2		18.2					1.017	+0.014	+5.9
	32	0.07	9.3	0.7	81.8			1			1000	1.018	+0.015	+6.3
	16	5.3	9.4	50.1	9.2			18.1		100		1.000	-0.003	-1.4
	12	3.8	9.4	35.4	9.2			32.0				0.998	-0.005	-2.8
	17	2.2	9.4	20.6	9.2			45.7		1 8	1	0.998	-0.005	-2.3
	14	0.07	9.4	0.7	9.2			63.9				0.995	-0.008	-3.0

⁸At densities corresponding to the atomic densities tabulated by YOM. (1) These are also used for ANL Set 635.

The average value of the computed k is 1.003.

CUsing the (△WM)/(△k/k) values of Table Ⅲ.

For completeness, the central spectra and the central spectral indices (principally fission ratios) were calculated; these are given in Appendix III. The group fission cross sections used in calculating the

The DSN Calculations

The homogeneous appreciate critical missaux given in Table IV were unce cognitive with the outer demperature to compute the expected smilest had it. U.S. At calculations were then contract out to obtain to offering evenly cash system. In all cases, the six closed outer and the expected out to core and loan the religion. In live cases, the cast distance appeared in the core and loan the religion. In live cases, the cast distance were expected with double the number of mean points, but this produced less than distance in a second traction of the expected with caseing in a case of the expected that expected and continued the expected and

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RESULTS OF THE CALCULATIONS

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average cross sections for U^{234} and U^{236} are not given by YOM, and values for these were estimated from the Second Edition of BNL-325. These are given in Appendix IV.

6. DISCUSSION OF THE CALCULATED VALUES OF k AND CONCLUSIONS

Examination of Table V shows that Set 635 is quite successful in that 17 of the calculated k values lie within $^{\pm}1\%$ of a mean value of 1.003, and the remaining 5 lie within $^{\pm}2\%$. This accuracy corresponds to an ability to predict the critical masses of 14 of the assemblies to better than $^{\pm}5\%$, and the remaining 8 to better than $^{\pm}10\%$.

If the nuclear data for a particular nuclide were appreciably in error, then it might be expected that there would be a tendency towards an increasingly inaccurate calculated value of k as the fraction of that nuclide was increased. The k values in Table V are grouped in a manner which would show such trends, but, although there are apparently slight tendencies, such as (a) a lower k as the U²³⁸/U²³⁵ ratio increases and (b) lower k than average for all the carbon-containing assemblies, it is doubtful if these trends are meaningful. The apparent absence of such trends does not necessarily mean that the nuclear data are correct as, for example, errors in the transport and capture cross sections of a nuclide could fortuitously cancel out in a k calculation. In addition, any trends would tend to be masked by random errors in the analysis.

In fact, the spread of calculated values of k is consistent with their being a statistical distribution, for the root-mean-square deviation from the mean value of 1.003 is 0.009, and 16 k values lie within ± 0.009 of the mean and the remaining 6 lie between 0.009 and 0.018.

Hence, to summarize, it appears that a single cross-section set is capable of predicting critical sizes with an accuracy of 5 to 10%. This result, although encouraging, should be treated with caution, and it is perfectly feasible that the procedures adopted here have inadvertently obscured errors and that these errors may be magnified in somewhat different systems.

ACKNOWLEDGEMENTS

The author wishes to thank F. W. Thalgott for his encouragement of this work and W. B. Loewenstein for valuable criticism of an early draft of this report. average cross sections for U²¹⁴ and U¹¹⁵ are not given by YOM, and values for those were estimated from the Second Divition of bNL-325. These are given in Appendix IV.

6. DISCUSSION OF THE CALCULATED VALUES OF

Exercimation of Table V shows that Set 515 is quite successful mother 17 of the calculated & values its within 12% of a mean value of 1,001, and the remaining 5 is within 12%. This accuracy corresponds to all the absence the critical masses of 14 of the assemblies to bester than 55%, and the remaining 8 to bester than 110%.

If the nuclear data for a particular nuclide wars appreciably included then it might be expected that their would be a tendency towards an increasingly concentrate relicitance value of k as the fraction of that a minimum available was increased. The howards in Table V are grouped in a manner which would show such frends, but, although there are apparently slight tendencies, such as (a) a lower k as the U^{AB}/100 ratio increases and you tendencies, such as (a) a lower k as the U^{AB}/100 ratio increases and you tendencies for all the carbon containing assemblines it is deathful if these trades are measurable. The apparent absence of such translated does not recessarily, maan that the suclear data are correct assistantly, errors in the trapsport and capture cross sections of a softer against could contributely cancel out in a k calculation. In addition, any manded could read to be masked by random errors in the analysis.

In fact, the excess of calculated values of k is consistent with their bots a statistical distribution, for the root mean aquare deviation from the mean value of 1,003 is 0.009, and 16 kyaldes is within 10,009 of the mean and the remaining to the between 0.009 and 0.016.

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ACKNOW LEDGEMENTS

The suffer wishes to thank F. W. Thalgott for his encouragement of this work and W. B. Loewenstein for yeluable critimam of an early drait of this report.

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APPENDIX I

REFERENCES FOR TABLE III

Assembly Number	Experimental Critical Mass	$\frac{(\triangle M/M)}{(\triangle k/k)}$	Hetero- geneous Correction	Irregular Boundary Correction	Center- gap Cor- rection	L/D
2A	14	14	14	14	14	14
5	14	a	14	14	14	14
6F	14	14	14	14	14	-
9A	14	14	14	14	14	-
10	14	14	14	14	14	1
11	14	14	a	14	14	14
12	14	14	14	14	14	14
14	14	14	14	14	14	14
16	14	14	14	14	14	14
17	14	14	a	14	14	14
20	1	c	a	a	a	1
23	17	d	a	a	a	17
24	17	e	a	a	a	17
25	g	g	a	a	a	g
29	17	g 2	a	a	a	17
30	3	3	3	a	a	3
31	18	18	18	a	a	18
32	17	ь	a	a	a	17
33	17	b	a	a	a	17
34	17	4	4	a	a	17
35	f	f	f	a	a	f
36	19	19	19	a	a	19

aEstimated by the author using results on similar reactors.

bTo be published as ANL reports.

CZPR-III Memo 61.

dZPR-III Memo 78.

eZPR-III Memo 76.

fZPR-III Memo 80.

⁸ZPR-III Memo 75.

AFPENDIX I

III ELIKAT ROZZEDRIKUTA

Estimated by the author using result

PR-III Mentolati

*ZFR-III Mente 784

ZPR III Memo-80.

SEPA-III Menig 75.

APPENDIX II

REACTOR COMPOSITIONS

ZPR-III				Vol	ume Percei	ntage of Ele	ment in Co	rea				Reflecto
Assembly Number	(18.75)	U238 (18.97)	Fe (7,85)	Ni (8.90)	Cr (6.91)	AI (2.70)	Na (0.84)	C (1.67)	0 (2.55)	Mo (10.19)	Zr (6.44)	Type b
2A	13.97	1.02	19.71	2.78	5.28	31.44			1000	1000		A
5	14.00	15.90	8.74	1.23	2.34	31.50			9 9			D
6F	14.00	15.90	8.81	1.24	2.36	31.40						A
9.4	11.70	38.00	10.19	1.43	2.73	21.50						A
10	11.85	57.90	13.82	1.95	3.70							A
11	9.51	71.72	6.55	0.92	1.75			100.00				A
12	9.38	35.40	6.55	0.92	1.75			31.96				A
14	9.38	0.70	6.55	0.92	1.75			63.92				A
16	9.38	50.10	6.55	0.92	1.75			18.10				A
17	9.38	20.60	6.55	0.92	1.75			45.68				A
20	6.09	18.97	10.26	1.44	2.75	25.14				5.03	4.32	8
23	9.27	0.70	6.51	0.91	1.74	42.82			376			A
- 24	7.57	72.90	6.68	0.94	1.79					100000		A
25	7.17	74.17	6.55	0.92	1.75							A
29	4.97	9,97	17.70	2.49	4.74	24.40			14.50	1		A
30 31	5.91	9.04	17.56	2.47	4.70	23.35			7.26			A
	5.81	9.14	17.58	2.48	4.70	23.49	4					A
N	9.26	0.66	58.05	8.18	15.54				100	100		A
33	9.27	0.68	45.58	6.42	12.20		18.20			100		A
34	4.67	10.30	17.63	2.48	4.72	25.50		9.08		1000000		A
35 36	4.06	0.29	35.52	5.00	9.50		35.56		4.15			C
36	9.37	49.51	9.09	1.28	2.43		18.23		- 4			A

(a) At densities given in parentheses for each element igm cm⁻³).

(b) In all cases the reflector was 30.00 cm thick. There were four types with the following volume percentage compositions:

	U235	U238	Fe	NI	Cr	Na	Al	Mo	
A	0.19	83.30	5.20	0.73	1.40	7.77			
В	0.10	45.39	13.92	1.96	3.72		10.08	2.46	
C	0.09	39.61	13.52	1.90	3.62	32.48		2.18	
D	∫0.08	39,70	5.24	0.74	1.40		24.60		Inner (18.1 cm thick)
ν	0.19	83.30	5.24	0.74	1.40		2.27		Outer (18.1 cm thick)

APPENDIX III

					1	1		0	ENTRAL S	PECTRA A	ND SPEC	TRAL IND	ICES /	1	200			1				
Assembly	2A	5	6F	9.4	10	11	12	14	16	17	20	23	24	25	29	30	31	×	33	м	35	36
Group										0	entral Spe	ctral Ind	ces									
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15	0.036 0.072 0.116 0.147 0.177 0.162 0.118 0.078 0.054 0.028 0.000 0.004	0.037 0.068 0.104 0.145 0.184 0.173 0.078 0.051 0.028 0.006 0.004	0.036 0.067 0.102 0.143 0.183 0.125 0.081 0.052 0.028 0.003 0.003	0.027 0.049 0.076 0.129 0.193 0.193 0.093 0.052 0.035 0.008	0.024 0.041 0.065 0.121 0.204 0.207 0.147 0.098 0.046 0.034 0.007 0.005	0.020 0.034 0.053 0.109 0.219 0.2157 0.108 0.048 0.043 0.008	0.026 0.048 0.073 0.112 0.156 0.156 0.130 0.102 0.074 0.057 0.030 0.020 0.010	0.036 0.074 0.112 0.118 0.118 0.108 0.096 0.080 0.072 0.058 0.041 0.032 0.022 0.014 0.011	0.023 0.041 0.064 0.111 0.173 0.177 0.143 0.107 0.067 0.052 0.021 0.013 0.005 0.002	0.030 0.057 0.086 0.114 0.140 0.134 0.117 0.094 0.076 0.059 0.037 0.037 0.015 0.008	0.020 0.038 0.065 0.111 0.169 0.185 0.151 0.007 0.071 0.053 0.016 0.011 0.002	0.036 0.072 0.112 0.144 0.162 0.156 0.120 0.080 0.062 0.038 0.011	0.017 0.029 0.046 0.099 0.193 0.214 0.163 0.116 0.052 0.050 0.010 0.009	0.016 0.028 0.044 0.097 0.191 0.214 0.118 0.054 0.052 0.011 0.009	0.019 0.039 0.066 0.100 0.141 0.146 0.108 0.087 0.072 0.033 0.023 0.011 0.005 0.004	0.021 0.044 0.076 0.114 0.160 0.162 0.161 0.102 0.076 0.057 0.022 0.010 0.005 0.005	0.022 0.044 0.077 0.123 0.174 0.179 0.096 0.068 0.069 0.015 0.015	0.019 0.041 0.080 0.125 0.195 0.187 0.187 0.092 0.062 0.037 0.011 0.009 0.001	0.021 0.046 0.088 0.128 0.186 0.135 0.092 0.061 0.034 0.011 0.008 0.002 0.001	0.018 0.038 0.067 0.107 0.148 0.155 0.102 0.082 0.069 0.033 0.028 0.011 0.005	0.015 0.033 0.065 0.096 0.143 0.167 0.146 0.084 0.059 0.027 0.025 0.011 0.006	0.02 0.04 0.06 0.11 0.19 0.29 0.15 0.10 0.05 0.03 0.00 0.00
16							0.001	0.008		0.002	antest Co	ne Contin	0		0.001			0.001	0.001	0.001	0.003	
σ, υ235	1.387	1.384	1.385	1.402	1.399	1.420	1.537	1.701	1.480	1.5%	1.462	1.411	ns (barns)	_	1						_	-
σ, UZ33	2.171	2.172	2.175	2.214	2.219	2.253	2.379	2.553	2.317	2.444	2.296	2.200	1.438	1.443	1.591	1.497	1.450	1.431_	1.424	1.582	1.595	1.414
σ, Pu239	1.791	1.785	1.784	1.773	1.765	1.763	1.815	1,909	1.788	1.846	1.779	1.796	2.281	2.288	2.455	2.333	2.274	2.255	2.242	2.465	2.465	2.240
σγ Pu240	0.7319	0.7123	0.7028	0.6107	0.5759	0.5202	0.5435	0.6324	0.5295	0.5711	0.5203	0.7089	0.4784	1.763 0.4678	1.825 0.4776	1.797	1.784	1.780	1.782	1.824	1.827	1.76
or U234	0.7137	0.6978	0.6892	0.6078	0.5795	0.5284	0.5376	0.6095	0.5293	0.5586	0.5206	0.6894	0.4764	0.4076	0.4776	0.5417	0.5711	0.5866	0.6076	0.4924	0.4602	0.550
O1 U236	0.2571	0.2446	0.2403	0.1898	0.1680	0.1433	0.1772	0.2415	0.1611	0.1995	0.1563	0.2524	0.1260	0.1217	0.1514	0.1721	0.1782	0.1762	0.6028	0.4883	0.4599	0.556
or U238	0.1172	0.1102	0.1081	0.0807	0.0692	0.0573	0.0778	0.1159	0.0680	0.0911	0.0649	0.1154	0.0494	0.0473	0.0650	0.0738	0.1762	0.1762	0.0804	0.0644	0.13%	0.161
σ _c U238	0.1413	0.1418	0.1423	0.1520	0.1533	0.1607	0.1843	0.2135	0.1731	0.1948	0.1696	0.1474	0.1667	0.1684	0.1998	0.1760	0.1647	0.1603	0.1570	0.1977	0.2012	0.067
				-							Central	Spectra				0.1700	0.1041	0.1003	0.1570	0.1977	W.EULE	u.Di
01 3015	1.565	1.569	1.570	1.579	1.587	1.587	1.548	1.501	1.566	1.532	1.571	1.559	1.586	1.586	1.543	1.559	1.569	1.576	1.574	1.545	1.545	1.584
01 4015	1.291	1.290	1.288	1.264	1.262	1.242	1.181	1.122	1.208	1.156	1.217	1.273	1.226	1.222	1.147	1.201	1.231	1.244	1.251	1.153	1.145	1.750
01 0015	0.528	0.514	0.508	0.436	0.412	0.366	0.354	0.372	0.358	0.358	0.356	0.502	0.333	0.324	0.300	0.362	0.394	0.410	0.427	0.311	0.288	0.391
01 4015	0.514	0.504	0.498	0.433	0.414	0.372	0.350	0.358	0.358	0.350	0.356	0.489	0.341	0.332	0.298	0.359	0.391	0.409	0.423	0.309	0.288	0.394
न धन् ५	0.185	0.177	0.174	0.135	0.120	0.101	0.115	0.142	0.109	0.125	0.107	0.179	0.0876	0.0844	0.0951	0.115	0.123	0.123	0.133	0.0971	0.0875	0.114
01 8015	0.0844	0.07%	0.0781	0.0575	0.0495	0.0404	0.0571	0.0681	0.0460	0.0571	0.0444	0.0818	0.0343	0.0328	0.0409	0.0493	0.0517	0.0509	0.0565	0.0407	0.0367	0.047
σ _c 8σ ₁ 5	0.102	0.102	0.103	0.108	0.110	0.113	0.122	0.126	0.117	0.122	0.116	0.105	0.116	0.117	0.126	0.118	0.114	0.112	0.110	0.125	0.126	0.111

APPENDIX IV

GROUP FISSION CROSS SECTIONS FOR U234 AND U236

These were estimated from the Second Edition of BNL-325.

Group	of U ²³⁴ (barns)	of U ²³⁶ (barns)
1	1.55	0.90
2	1.50	0.94
3	1.50	0.74
4	1.15	0.46
5	0.90	0.02
6	0.25	
7	0.06	
8		
9		
10		
11		
12		
13		
14		7 (3)
15		
16		

A PERSONAL TANKS IN

TROUP FISSION CROSS SECTIONS FOR UPLANTABLE

hese were estimated from the Second Edition of BML-82

